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Ring-Plane Traveling-Wave Tube Slow-Wave Circuit Design Simulations at V-Band Frequencies

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ABSTRACT

The V-Band frequency range of 59-64 GHz is a region of the millimeter-wave spectrum that has been designated for inter-satellite communications. As a first effort to develop a high-efficiency V-band traveling-wave tube (TWT), variations on a ring-plane slow-wave circuit were computationally investigated to develop an alternative to the more conventional ferruled coupled-cavity circuit. The ring-plane circuit was chosen because of its high interaction impedance, large beam aperture, and excellent thermal dissipation properties.

A prototype ring-plane TWT slow-wave circuit conceived by White et al. (ref. 1) is shown in figure 1. With a 98 kV, 3.7 ampere electron beam, this circuit produced 43 kW peak power at 33 GHz (ref. 2).

Despite the high-power capabilities of the ring-plane TWT, disadvantages of low bandwidth and high voltage requirements have until now prevented its acceptance outside the laboratory. In this paper, we use the three-dimensional electromagnetic simulation code MAFIA to investigate methods of increasing the bandwidth and lowering the operating voltage. Dispersion, impedance, and attenuation calculations for various geometric variations and loading distributions were performed. Based on the results of the variations, a circuit termed the finned-ladder TWT slow-wave circuit was designed and is compared here to the scaled ring-plane prototype and the conventional ferruled coupled-cavity TWT circuit over the V-band frequency range.

INTRODUCTION TO MAFIA

MAFIA (Solution of MAxwell's equations by the FInite-Integration-Algorithm) is a powerful modular electromagnetic simulation code used for the computer-aided design and analysis of fully three-dimensional and two-dimensional electromagnetic devices, magnets, RF cavities, waveguides, antennas, etc. (refs. 3 and 4). The 3.2 version of the code includes the following nine modules (those designated with * were used in this study):

- | | |
|-----------|---------------------------------|
| - M* | Mesh Generating Preprocessor |
| - S | Electro- and Magneto-Statics |
| - E* | Frequency Domain |
| - W3 | Eddy Currents |
| - T2/T3 | Time Domain |
| - TS2/TS3 | Particle-in-Cell (PIC) Programs |
| - P* | Postprocessor |

ANALYSIS

MAFIA was used to calculate the frequency-phase dispersion, beam on-axis interaction impedance, and attenuation for the prototype and several variations of the ring-plane TWT circuit. The prototype transverse mesh is shown in figure 2.

The frequency-phase dispersion characteristics were obtained by using the quasi-periodic boundary condition of MAFIA. This feature of the code allows the user to choose a fixed phase advance per cavity in the direction of periodicity, enabling exceptionally accurate dispersion curve calculations.

The beam on-axis interaction impedance is a measure of the strength of interaction between a RF wave harmonic and the electron beam. The method for calculating the beam on-axis interaction impedance with MAFIA is similar to experimental methods where ω - β characteristics are determined by measuring the resonant frequencies in a section of circuit shorted at both ends. Truncating an infinite circuit at two points with either an electric or magnetic wall with MAFIA corresponds to simulating standing waves with an integral number of half-wavelengths (phase shifts of π) within the isolated circuit section.

The necessary input for the attenuation calculations includes specifying a conductivity value for conducting materials. Because actual losses in a circuit are consistently more than the theoretically predicted values due to surface irregularities, an effective conductivity value, acquired by matching simulated results to estimated results for a coupled-cavity TWT slow-wave circuit, was used in the calculations (ref. 5).

RING-PLANE PROTOTYPE VARIATIONS

This study focuses on a circuit design in the V-Band frequency range of the millimeter-wave spectrum that has been designated for inter-satellite communications where large bandwidth, high efficiency and modest weight are important. The scaled prototype ring-plane circuit has a small bandwidth and operates at an extremely high voltage, thus requiring a large power supply.

The finned-ladder slow-wave circuit was developed from the results of several simulated variations of the scaled prototype ring-plane circuit in order to alleviate the above mentioned concerns. The modifications made to the ring-plane circuit include an enlarged outer barrel diameter, slots introduced in the support planes, and metal fins included as a loading method.

Outer Barrel

In order to decrease the operating voltage by decreasing the phase velocity of the circuit, the outer cylindrical barrel diameter D was enlarged (fig. 1). Existence of a barrel around the circuit provides the low frequency cutoff point, so by increasing the barrel diameter from the prototype dimension, an accompanying decrease in this lower cutoff frequency occurs without a significant effect on the upper cutoff, thus increasing the cold bandwidth of the circuit. This is explained by the high concentration of the electric fields between the rings of the circuit at high frequencies versus a field distribution more throughout the region between the rings and the barrel at low frequencies (fig. 3). The enlarged barrel variation, therefore, will have greater effects on the field pattern at lower frequencies, thereby selectively altering the lower cutoff. Limitations inherent to focusing considerations are placed on the barrel diameter variations. As the barrel is placed farther away from the circuit, problems may arise with the weight of necessarily stronger focusing magnets.

Fin Loading

To further widen the bandwidth of the circuit and reduce the operating voltage, common loading schemes were investigated. By adding metal fins with width f to the outer barrel, as shown in figure 4, the fields are perturbed more at lower frequencies than at higher values (as mentioned previously), allowing for control of the dispersion. The loading fins and barrel diameter increase did have a large effect on the reduction of operating voltage and increase in cold circuit bandwidth, as is apparent in figure 5. The distance, s , between the ring and fin was made as small as possible (taking manufacturing issues into consideration), as this dimension provided the maximum effect on slowing circuit phase velocity and broadening bandwidth.

Slot Length

Unfortunately both the barrel enlargement and fin loading caused a corresponding reduction in the beam on-axis interaction impedance. To counteract for this decrease in impedance, slots with length L were added to the support planes (fig. 6). The support planes of the ring-plane circuit cause the electric field between rings to go to zero azimuthally at the supports. These regions of zero field cause a corresponding decrease in the axial electric field, thus decreasing the beam on-axis interaction impedance. By slotting the support planes, the zero field condition is removed permitting a larger axial electric field to exist. This results in a significant increase in the impedance as shown in figure 7.

Finned-Ladder TWT Slow-Wave Circuit Design

Figure 8 shows a MAFIA three-dimensional view of the circuit termed the finned-ladder circuit with the modifications described above. Figure 9 shows a MAFIA three-dimensional electric field plot of a zoomed in portion of the finned-ladder circuit at a phase shift per cavity of 45 degrees where the arrow size is proportional in size to the magnitude of the field. The high concentration of the electric field between the rings at a low frequency is illustrated here. Figure 10 shows another MAFIA plot which contours the losses of the circuit, the highest loss represented by red. From the figure it is seen that the highest concentration of losses is in the slots.

SIMULATED RESULTS

961HA Ferruled Coupled-Cavity

In order to compare the ring-plane prototype and finned-ladder circuits to the conventional ferruled coupled-cavity circuit, computations involving the combined use of three-dimensional and small-signal simulation codes were performed. The three-dimensional simulation code MAFIA was used to model the cavity designs and to accurately simulate the cold-test parameters. Figures 11 to 13 compare the cold-test results (dispersion, impedance, and attenuation, respectively) obtained using MAFIA to the experimental dispersion, impedance and estimated attenuation.

From the computed cold-test parameters, the small-signal gain is determined as a function of frequency. Figure 14 compares the computed small-signal gain using MAFIA cold-test results to experimental small-signal gain for the 961HA. The agreement is excellent, indicating that the calculations are accurate for the 961HA ferruled coupled-cavity TWT.

Finned-Ladder

To establish a meaningful comparison of the scaled ring-plane prototype and novel finned-ladder TWT's with the conventional ferruled coupled-cavity TWT, the ring-plane and finned-ladder circuits were designed with the same operating parameters as the 961HA listed in Table I. Because the total circuit length of each TWT is

undetermined, the small-signal gain per number of electronic wavelengths BC is compared for each case in figure 15. This plot shows that the finned-ladder circuit far exceeds the gain per number of electronic wavelengths and the bandwidth of the scaled ring-plane prototype circuit. Compared to the 961HA, the midband gain is far superior, with a moderate sacrifice in bandwidth.

CONCLUSIONS

The value of computer modeling in TWT development was demonstrated in the presentation of a novel, high gain, improved-bandwidth, finned-ladder TWT slow-wave circuit. This circuit shows a major improvement in beam interaction impedance, gain and bandwidth and a significantly reduced operating voltage compared to the scaled ring-plane prototype TWT, while retaining excellent thermal dissipation properties. Compared to the conventional coupled-cavity TWT, the finned-ladder TWT with similar design parameters shows a superior midband gain without a large sacrifice in bandwidth.

Further computational work is needed to investigate stability and manufacturing tolerances. It is expected that the time-dependent module of MAFIA can be used to design termination and output matches. A detailed circuit design will also require modeling the circuit with a large-signal coupled-cavity TWT computer code (ref. 6).

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TABLE I.—MAJOR DESIGN PARAMETERS
AT MID-BAND

Operating frequency	61.5 GHz
Beam voltage	20 kV
Beam current	74 mA
Beam radius/aperture radius	0.5

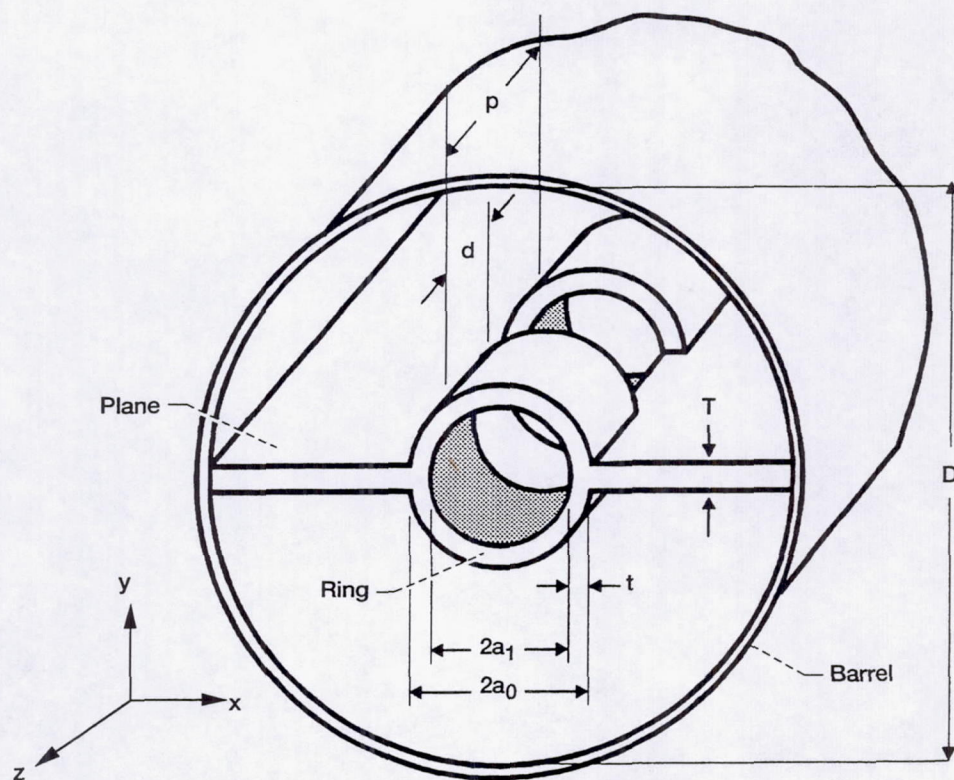


Figure 1.—Ring-plane prototype circuit.

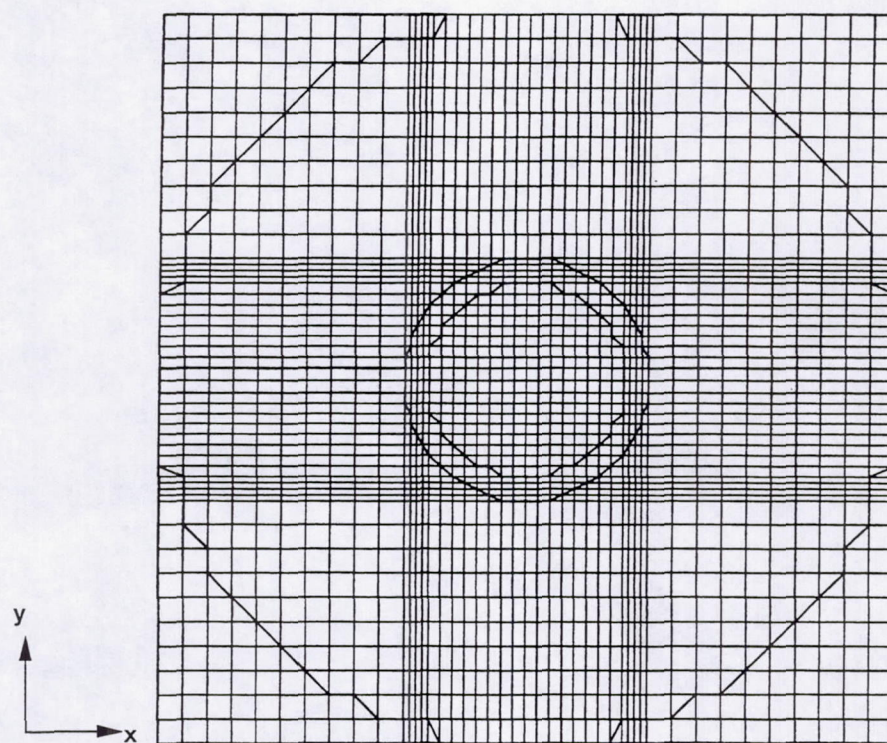


Figure 2.—MAFIA transverse grid of the ring-plane prototype circuit.

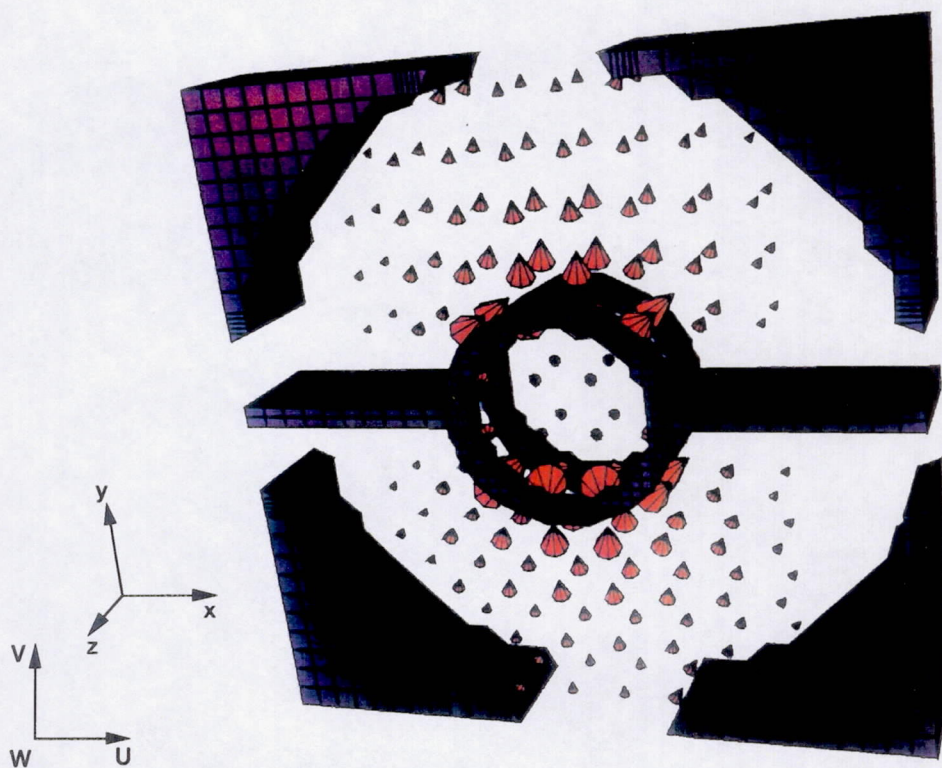


Figure 3.—MAFIA three-dimensional view of the electric field pattern at $\beta L = 45$ degrees.

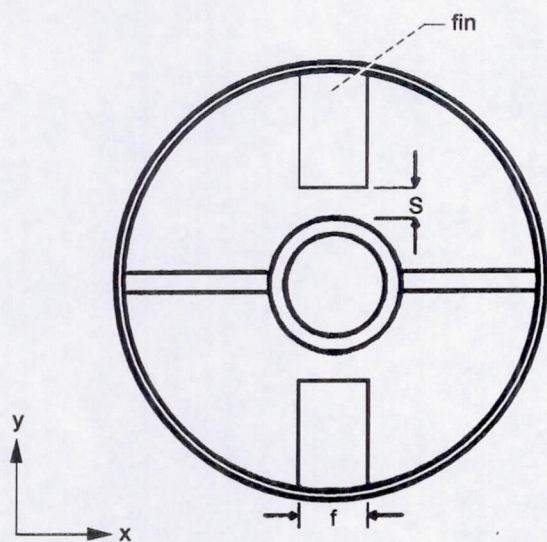


Figure 4.—Ring-plane circuit with fins.

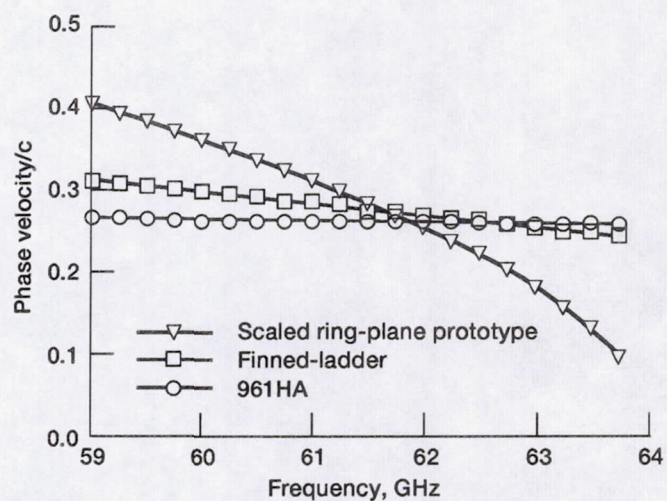


Figure 5.—Normalized phase-velocity of scaled ring-plane, finned-ladder, and 961HA ferruled coupled-cavity TWT slow-wave circuits at V-band.

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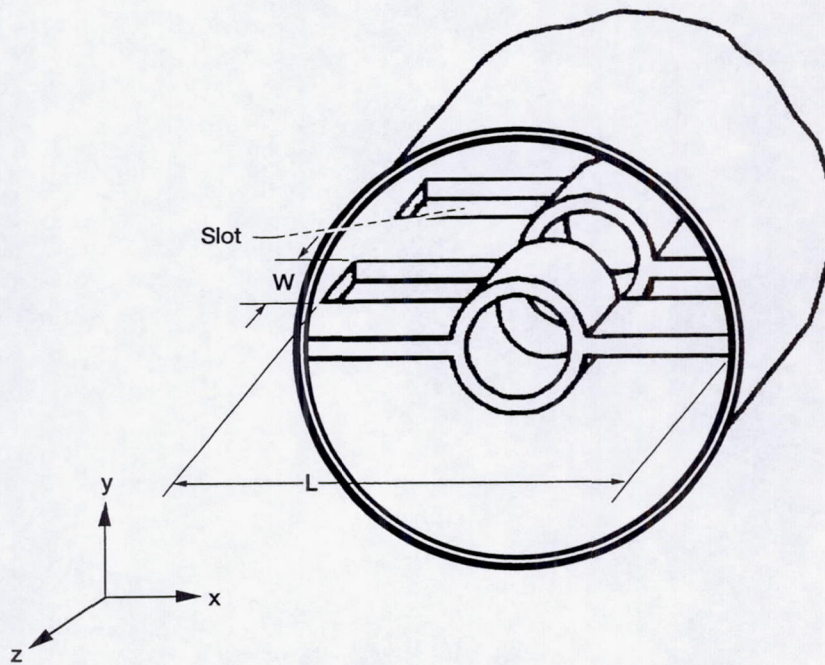


Figure 6.—Ring-plane circuit with slots.

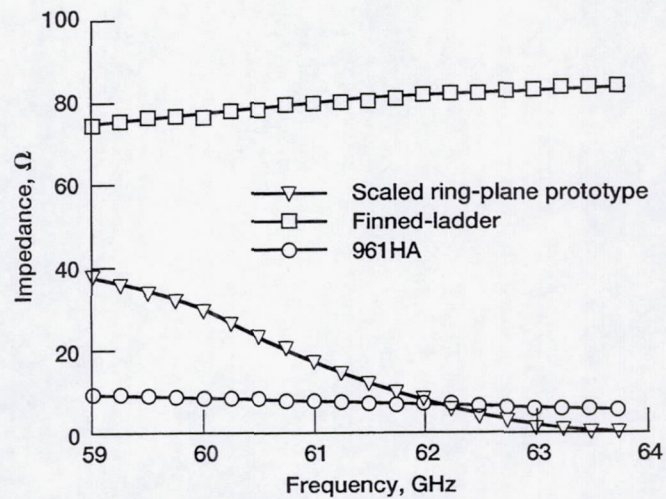


Figure 7.—Simulated beam on-axis interaction impedance of scaled ring-plane, finned-ladder, and 961HA ferruled coupled-cavity TWT slow-wave circuits at V-band.

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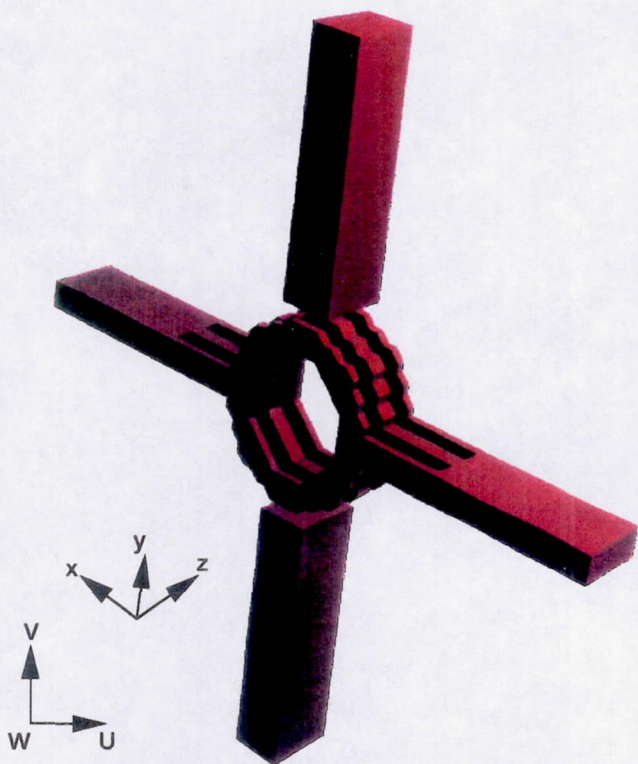


Figure 8.—MAFIA three-dimensional view of finned-ladder TWT slow-wave circuit.

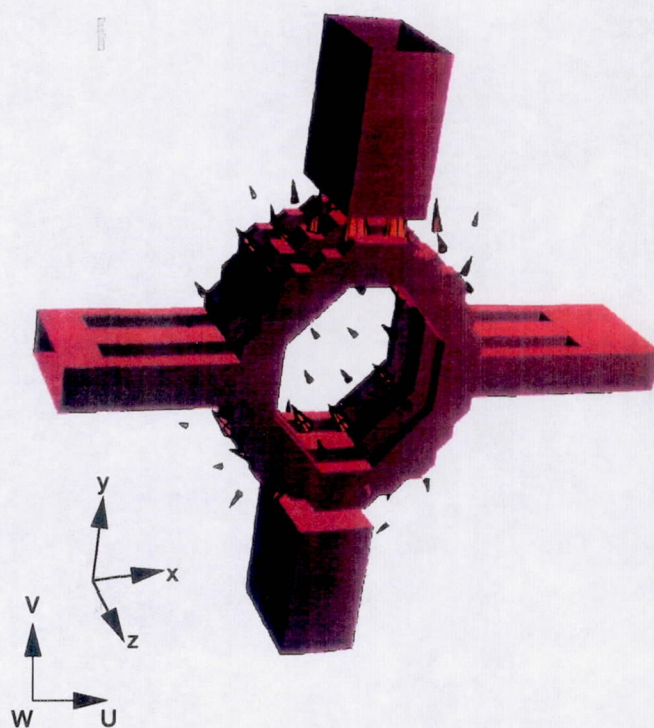


Figure 9.—MAFIA three-dimensional view of the electric field pattern at $\beta L = 45$ degrees for a zoomed in portion of finned-ladder circuit.

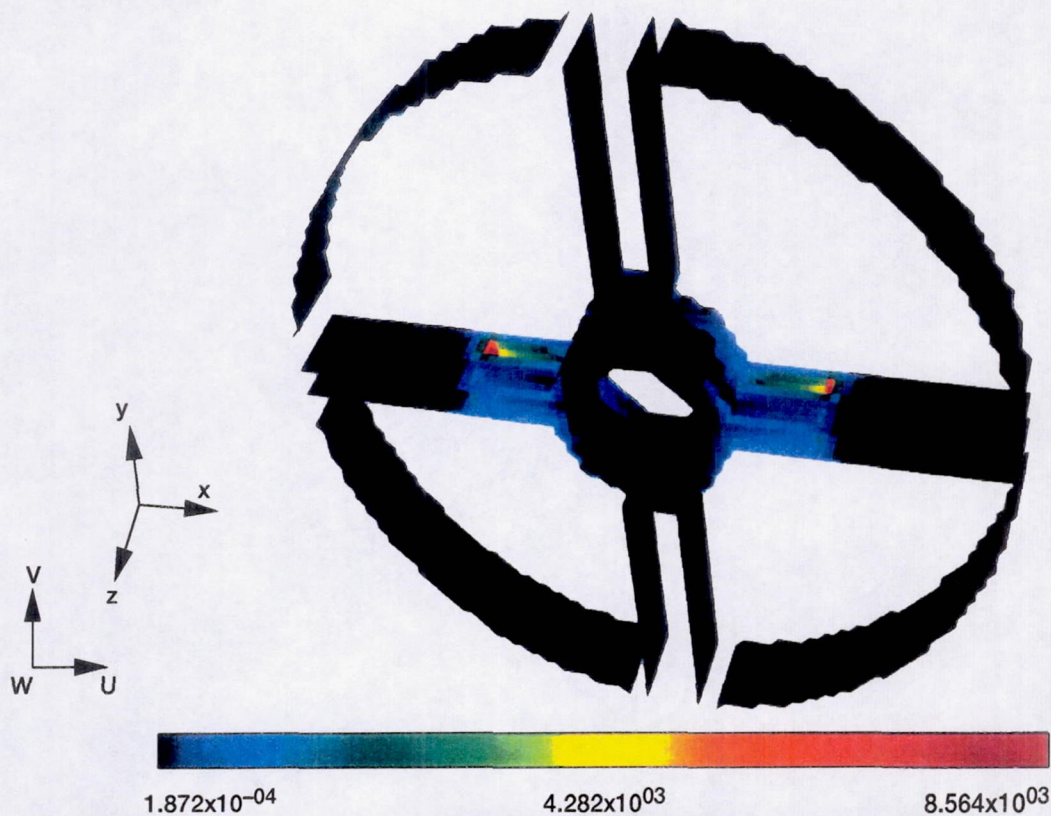


Figure 10.—MAFIA three-dimensional contour plot of losses for finned-ladder circuit.

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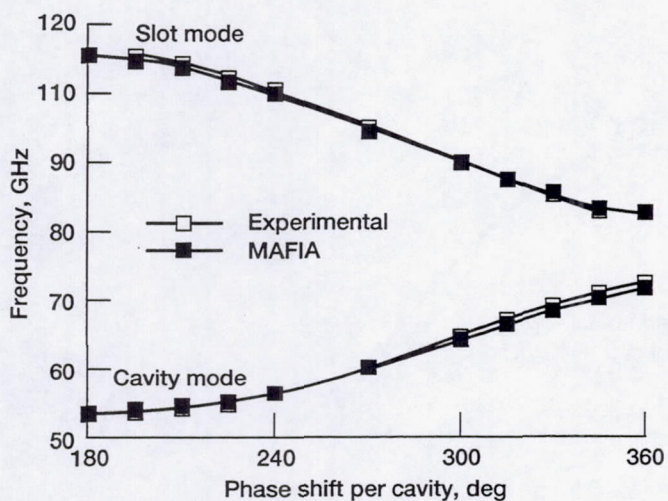


Figure 11.—Experimental and MAFIA simulations of dispersion for cavity and slot modes of Hughes 961HA TWT.

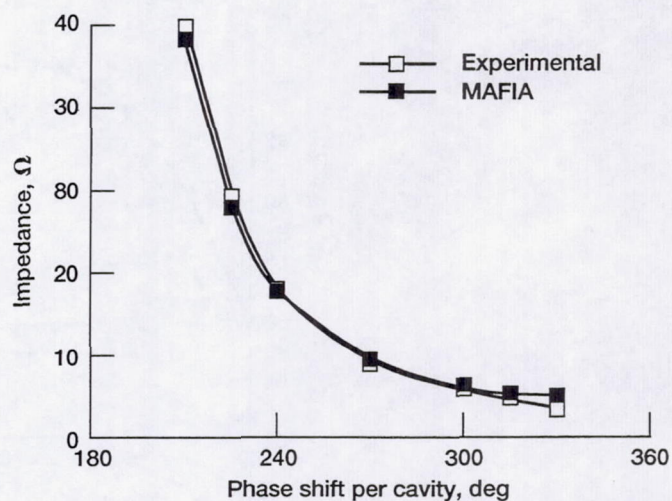


Figure 12.—Experimental and MAFIA simulations of beam on-axis interaction impedance for Hughes 961HA TWT.

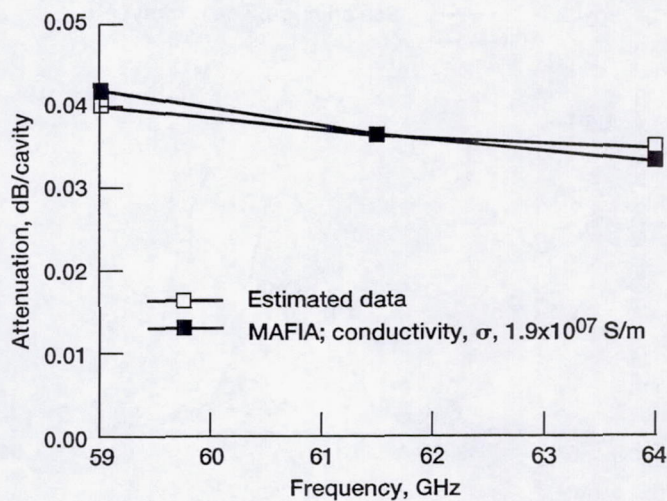


Figure 13.—Estimated and MAFIA simulations of circuit attenuation for Hughes 961HA TWT.

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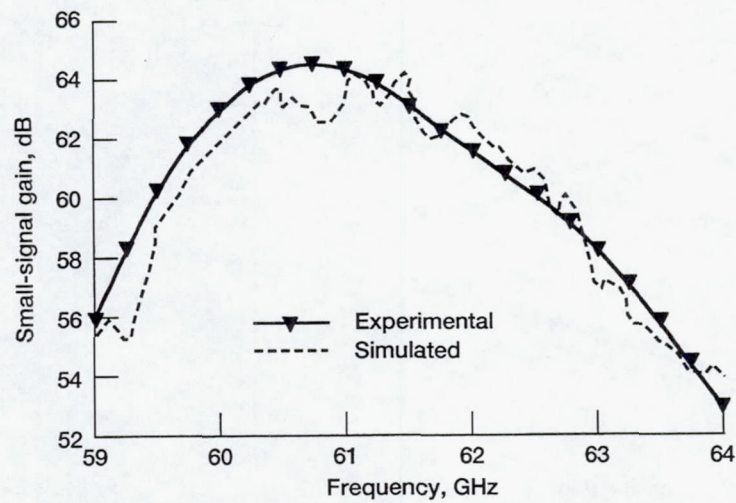


Figure 14.—961HA experimental small-signal gain compared to computed small-signal gain using MAFIA cold-test results.

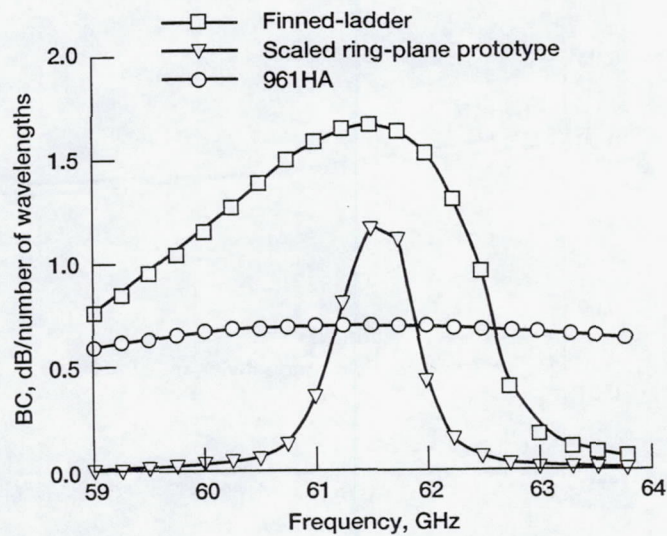


Figure 15.—Computed small-signal gain per number of electronic wavelengths using MAFIA cold-test parameters.

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